WHITE PAPER

Understanding Slab Refusals in Aluminum Hot Rolling: Causes and Solutions

BY PIERRE TALJAARD, LEAD PRODUCT APPLICATION MANAGER - NON-FERROUS

Introduction

Slab refusals are a common yet challenging issue in aluminum hot rolling. These refusals, which occur when a slab fails to be drawn into the roll bite, can disrupt production under seemingly normal conditions. Understanding the root causes of refusals and how to prevent them requires an in-depth look at the variables that influence rolling, such as rolling mill configuration, work roll setup, roll gap lubrication, and various process conditions.

In this white paper, we'll explore the fundamentals of slab refusals, the key factors that contribute to them, and practical solutions to address these issues in aluminum hot rolling.

The Fundamentals of Slab Refusals

At the heart of slab refusals is the interaction between the slab and the work rolls, specifically the forces that occur when the slab enters the roll gap.

To understand refusals, it is therefore necessary to understand the roll gap and the respective forces that interact at the point of first contact between the slab and the work roll surface. The forces at this point, and specifically the horizontal components of these forces, determine whether the slab is pulled into the roll bite or whether a refusal will occur. This is illustrated at the hand of the roll gap schematic in the Fig. 1.

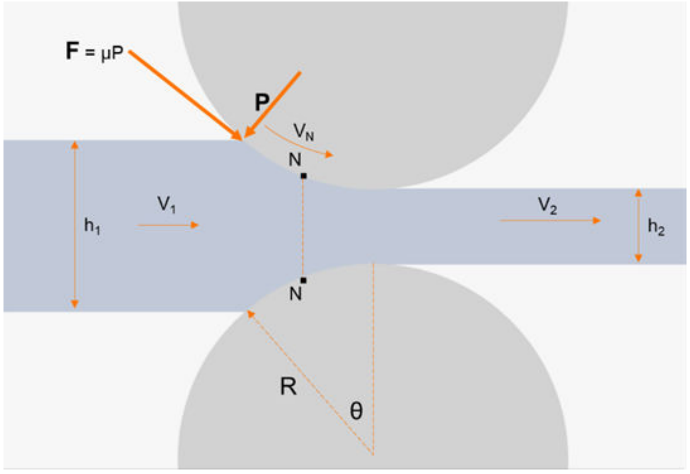

Fig. 1 The roll gap schematic

The variables in the above schematic are defined as follows:

- h1= Entry slab thickness
- h2= Exit slab thickness
- V1= Entry slab speed
- V2= Exit slab speed
- VN= Work roll circumferential speed
- N= Neutral point, where the work roll speed is equal to the slab speed
- R= Work roll radius
- **θ**= Contact angle
- μ= Coefficient of friction at the point of contact
- P= Radial force at the point of contact
- F= Friction force at the point of contact, with F=μP

At the point of entry into the roll gap the force between the work roll and the slab is governed by the normal force (**P**) and the friction force

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(**F**). **F** is the radial friction force at the point of contact and is equal to the coefficient of friction at the point of contact multiplied by the radial force (P) exerted by the work roll at the point of contact. The friction force must be high enough to provide traction for the metal to be drawn into the roll gap.

For this to happen the horizontal component of the friction force (**F.cosθ**) must be equal to or greater than the horizontal component of the normal force (**P.sinθ**), as illustrated in Fig. 2.

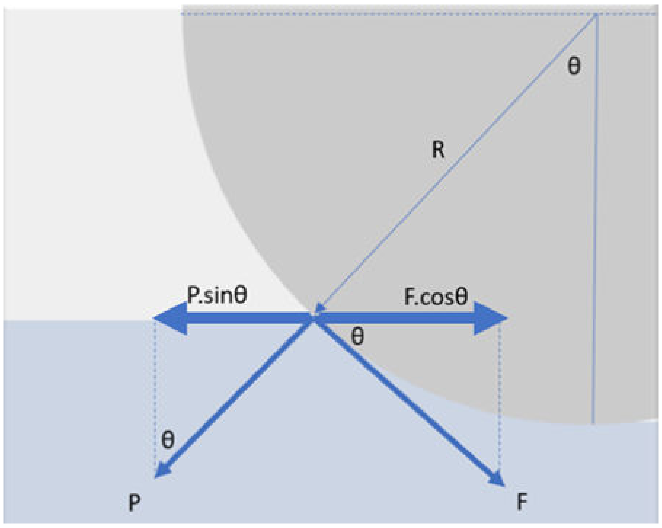

Fig. 2 Roll forces at the point of contact between the slab and the work roll

Therefore, refusals will occur when:

- $P.\sin\theta \geq F.\cos\theta$, and with $F = \mu P$*, when:
- $P.\sin\theta \geq \mu P.\cos\theta$

Therefore, when:

- $\frac{\sin\theta}{\cos\theta} > \mu$ or $\tan\theta > \mu$,

the metal cannot be drawn into the roll bite.

Refusals are therefore primarily governed by:

- the Contact angle (**θ**) and
- the Coefficient of friction (**μ**).

Several factors can influence the likelihood of refusals during rolling, and understanding these variables is crucial for root cause analysis. Here is a breakdown of the main factors:

The Contact Angle (Θ)

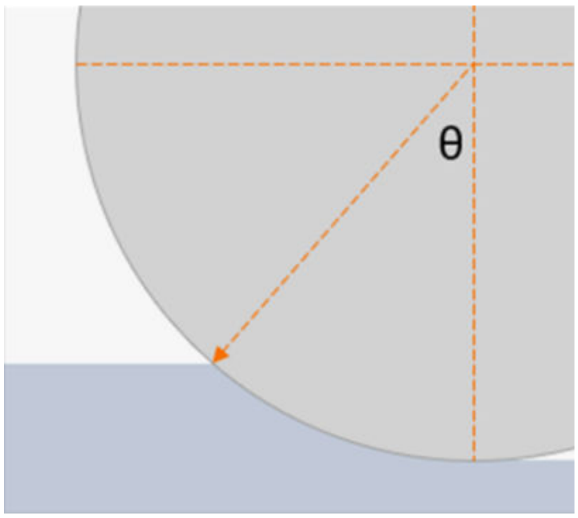

Fig. 3 The contact angle

The following variables impact on the contact angle (**θ**):

- The pass reduction
  - The absolute reduction in mm
- The work roll diameter
- The work roll position relative to the mill pass line (the work roll pass line set-up).
  - The position of the upper surface of the bottom work roll relative to the position of the pass line.

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The Coefficient of Friction (CoF) (μ)

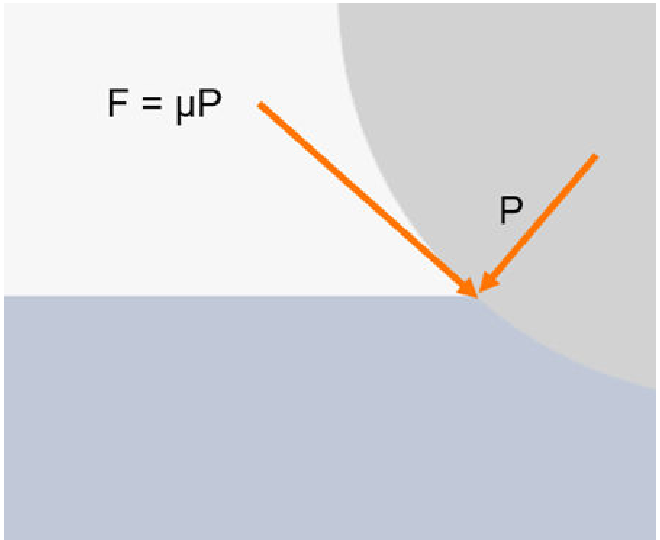

Fig. 4 The CoF at the point of contact

The following variables impact on the Coefficient of Friction (μ), and specifically the CoF at the point of contact between the slab and the work roll.

- The rolling fluid properties:
  - Emulsion concentration
  - Emulsion stability
  - Emulsion viscosity
  - Tramp oil contamination
- The work roll surface properties:
  - Work roll roughness
- The metal properties:
  - Alloy type (Metal yield stress)
  - Metal temperature

Coefficient of Friction and Maximum Absolute Reduction

For a given CoF and work roll diameter there is a limit to the maximum achievable absolute reduction before refusals will start.

The absolute reduction in mm per pass directly impacts on the contact angle; the higher the reduction, the bigger the contact angle, as illustrated in Fig. 5.

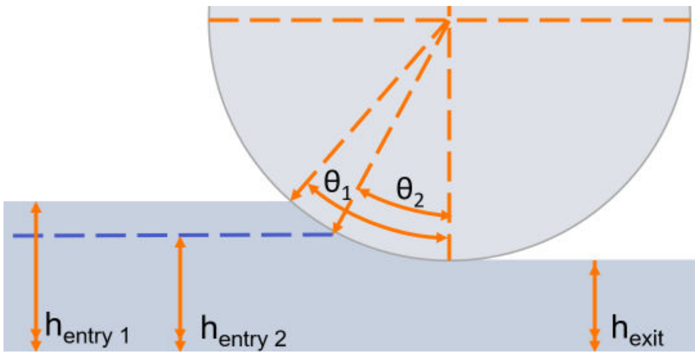

FIg. 5 Relationship between the contact angle and absolute reduction.

With rolling possible only when $\mu > \tan\theta$, any variable that impacts on the CoF will directly impact on the maximum achievable reduction.

The CoF at the point of contact between the slab and the work roll will determine the maximum absolute reduction possible for a fixed work roll diameter. The impact of CoF on the maximum achievable absolute reduction is represented in the Fig. 6, for a work roll diameter of 800 mm.

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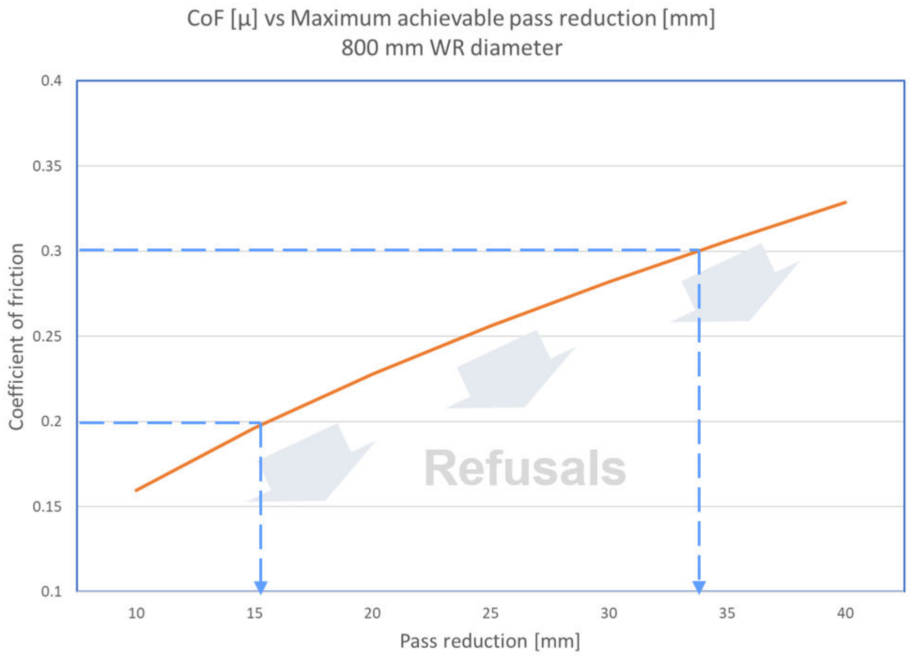

Fig. 6 The impact of CoF on the maximum achievable reduction

This illustrates the impact that an unforeseen reduction in CoF may have on the achievable reduction, and hence may result in unexpected refusals.

Changes in CoF are readily brought about by contamination from equipment lubrication and hydraulic oil systems, reduction in work roll roughness, and emulsions with varying stability.

Work Roll Diameter Impact

Modern hot roughing mills are typically designed with work roll diameters in the range of 800-1000 mm. Mills designed with smaller work rolls require a higher CoF to achieve the same reductions as larger diameter work rolls.

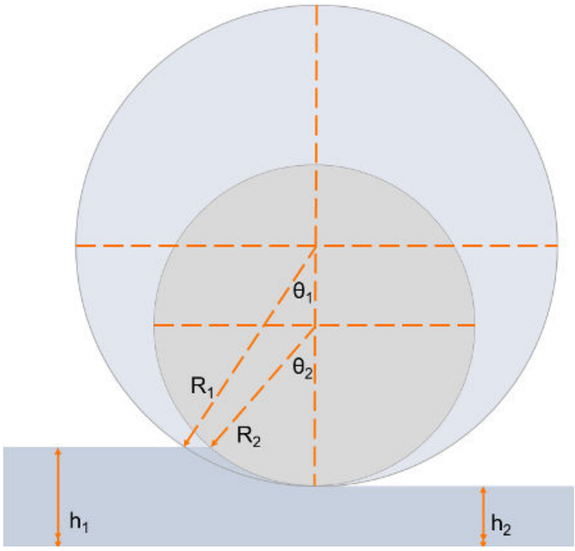

Fig. 7 The impact of WR diameter on the contact angle

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With a decrease in work roll diameter (R2< R1) the contact angle increases for the same absolute reduction h1- h2.

- With **θ**2>**θ**1,
- Tan**θ**2> Tan**θ**1,and
- μ2> μ1
  - With a smaller WR diameter a higher coefficient of friction is required to achieve the same maximum reduction, or
  - With the same coefficient of friction (μ), a bigger reduction is possible for a larger diameter work roll, before refusals will occur, sinceTan**θ**1< Tan**θ**2

The graph in FIg. 8 illustrates the effect on maximum reduction, with the same CoF. For a CoF of 0.25 this will result in a maximum reduction of 23.5 mm for an 800 mm WR, versus 29.5 mm for a 1000 mm WR. This results in a difference in maximum reduction of 6 mm, or roughly a 20% loss in pass reduction capability.

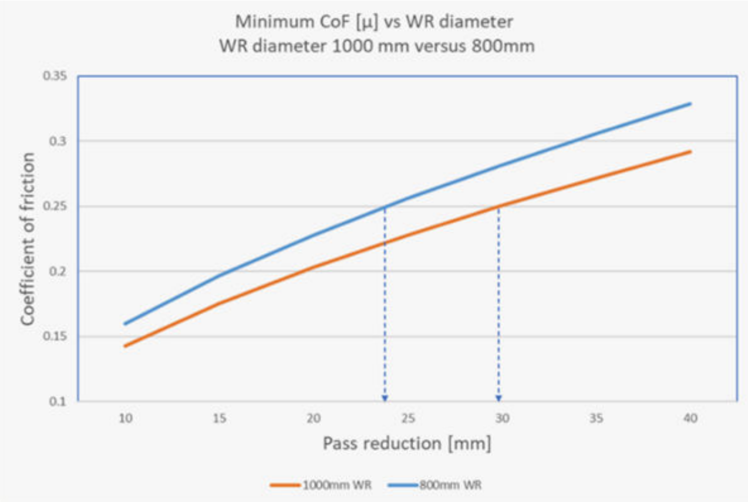

Fig. 8 The impact of WR diameter on the maximum achievable reduction.

During the life cycle of a work roll there is a reduction in diameter. Work rolls are generally designed with a useful surface hardness profile that extends roughly 30 mm into the roll, therefore the difference in diameter of a new roll and a roll towards the end of its life cycle is approximately 60 mm. From the graph shown in Fig. 9 it is clear that the impact on maximum reduction is small (less than 2 mm), with all other variables constant and the CoF = 0.25.

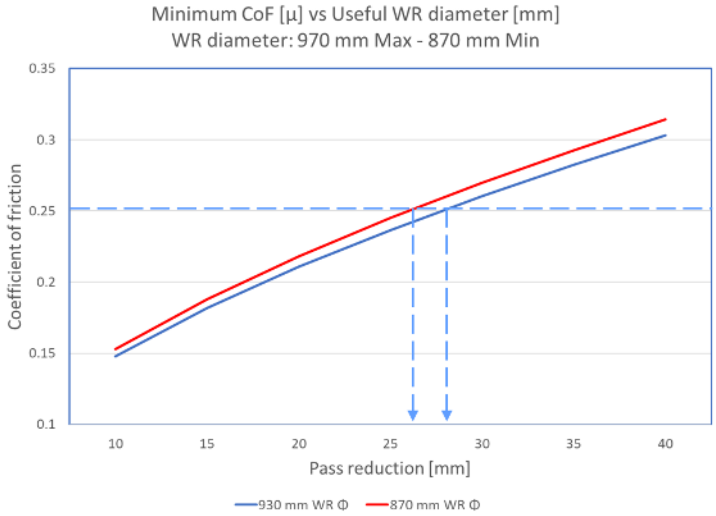

Fig. 9 Impact of WR diameter reduction on maximum achievable reduction.

Note: All the above analyses assume that the pass line set-up of the work rolls are perfectly aligned to the slab pass line.

This analysis shows that the reduction in WR diameter over its lifecycle does not contribute significantly to refusals in hot rolling.

As will be illustrated in the next section, it is rather the change in WR pass line height when changing from larger diameter to smaller diameter work rolls (or vice versa), without correcting the work roll pass line height, that impacts significantly on refusals.

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The Mill Pass Line

The mill pass line is defined as the line that runs through the centerline of the slab, as illustrated in Fig. 10. To achieve optimized rolling conditions the top and bottom work should ideally be continuously adjusted in height to ensure that the mid-point of the roll gap coincides with the mill pass line, i.e., the center line of the slab.

- To achieve this the bottom work roll needs to be adjusted in height to compensate for the change in absolute reduction from pass to pass.
- At the same time the top work roll needs to be continuously adjusted to compensate for both the change in absolute reduction from pass to pass and the reduction in slab thickness.

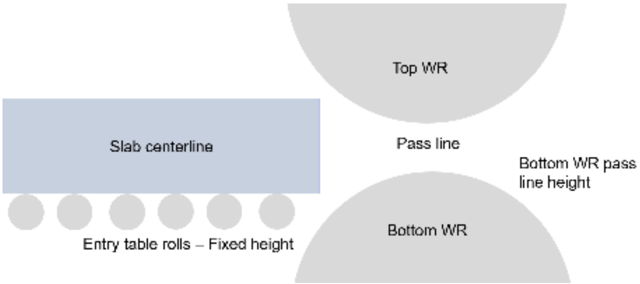

Fig. 10 The rolling mill pass line

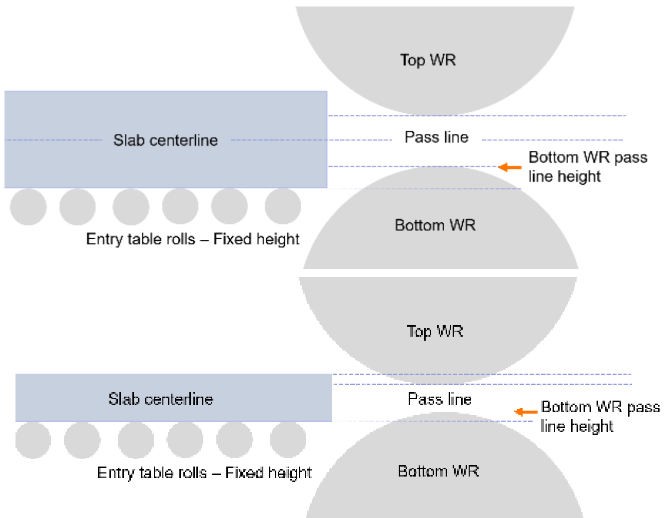

Fig. 11 Adjustment of WR pass line relative to slab pass line to accommodate changes in slab thickness and absolute reduction

Modern hot rolling mills have both mechanical and hydraulic bottom work roll adjustment systems to continuously make small adjustments to the bottom work roll passline height.

Older rolling mills often only have mechanical wedges or spacer bars that are adjusted after every work roll change to set up a fixed bottom work roll passline position. When this adjustment is not done, or incorrectly done, it can have a major impact on the occurrence of refusals, and it is often at the root cause of refusals. The impact of a work roll passline that is offset from the mill passline is illustrated in Fig. 12 for a work roll diameter of 900 mm, at respectively 2-, 4-, 6- and 8-mm offset from the mill passline.

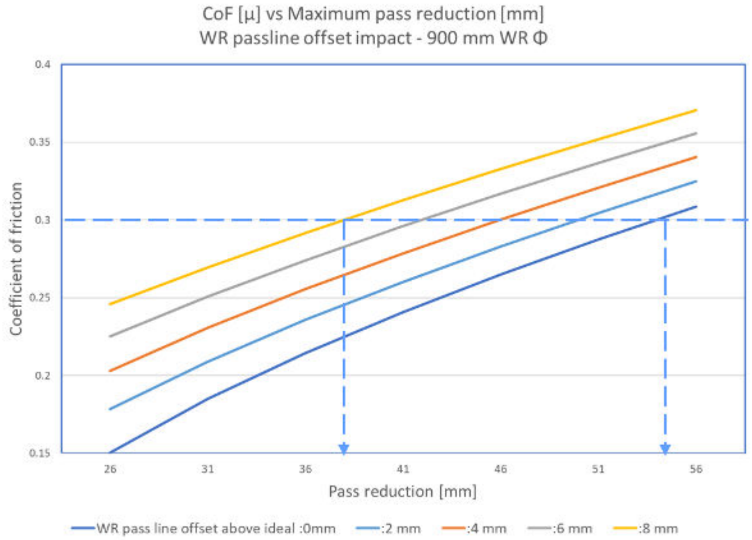

Fig. 12 Impact of an offset of the WR pass line from the slab pass line on the maximum achievable absolute reduction

In this example an 8 mm offset in WR pass line set-up can result in reducing the maximum achievable absolute reduction by 16,5 mm. In this case a reduction from 37,5 mm to 21 mm, i.e., approximately 45%.

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From this it is clear that WR pass line set-up is one of the major process variables impacting on refusals. This becomes important to consider when doing a roll change, say from new (larger diameter) work rolls to old (smaller diameter) work rolls.

If the bottom WR pass line is not set up correctly for the new (lower diameter) WR, it could have a significant impact on refusals even when the diameter is only a smaller by a few millimetres. This is the reason why refusals often occur after WR changes. As such, it is not the difference in WR diameter that is causing the refusals, but rather the change in WR pass line brought about by the difference in WR diameter.

Note: The same argument applies when changing from a smaller to a larger diameter WR.

Pass line variation with slab width changes

The impact of a change in the slab width on the slab pass line is often overlooked. The relative vertical position of the slab can vary when the table rolls are tapered, which is the case for most modern rolling mills. The change in slab pass line is illustrated in Fig.13 below.

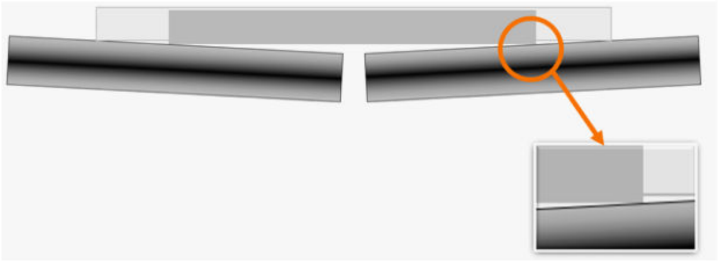

Fig. 13 Pass line change as a result of slab width change on a tapered roller table

Table 1 The change in slab pass line from the reference pass line (1 800 mm slab width) for a roller table with a 1:25 taper.

Slab width [mm]	Pass line change	Remarks
1800	0	Reference pass line
1600	-4	
1400	-8	
1200	-12	

Table 1 shows the change in slab pass line from the reference pass line (1 800 mm slab width) for a roller table with a 1:25 taper.

A change in slab width during a rolling campaign on a set of work rolls may therefore result in refusals if the work roll pass line is not adjusted according to the slab width and the specific roller table design.

Coefficient of Friction (CoF)

Since the conditions for refusals are controlled by the equation **$\mu > \tan\Theta$** it is important to understand which factors can impact on the coefficient of fraction (CoF) at the point of entry.

It is not easy to calculate or measure the CoF for a specific set of variables. However, it is possible to calculate the relative entry film thickness for a particular set of variables. For this discussion, it is assumed that there is a proportional and inverse relationship between the entry film thickness and the CoF. i.e., the thicker the entry film thickness, the lower the CoF.

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The entry film thickness is calculated using the well-known Wilson-Walowit equation:

$$h_{itx} = \frac{3 \times \eta_{tx} \times \alpha_{tx} \times (N + V)}{1 - e^{-2/\mathrm{sqrt}(3) \times \alpha_{tx} \times (Y - S)}} \times \sqrt{\left(\frac{R}{(g_1 - g_2)}\right)} \times 10^6 \ (\mu m)$$

Where:

Variable	Unit	Description
hitx	µm	Entry film thickness at temperature tx
ηtx	Pa.s	Dynamic viscosity at temperature tx
αtx	1/Pa	Viscosity pressure relationship at temperature tx
N	m/s	Inlet sheet speed
V	m/s	Work roll speed
Y	Pa	Metal yield stress
S	Pa	Unwind tension (when applicable)
R	m	Work roll radius
g1	m	Inlet sheet thickness
g2	m	Outlet sheet thickness

This equation forms the basis used by Quaker Houghton to develop a roll gap lubrication model that illustrates the relative impact of various process variables on a normalized roll gap film thickness. Note: The graphs below indicate the normalized values and does not represent the absolute film thickness. These results give some indication on the relative magnitude that various process variables have on the film thickness, and hence the coefficient of friction (CoF).

Alloy rolled and metal temperature

Whilst the alloy rolled is a fixed variable it is useful to see what the impact is on possible refusals.

Fig. 14 below shows that, at a fixed slab temperature, the film thickness is relatively thicker for a soft alloy (3005) compared to a harder alloy (5182). Therefore, it is not uncommon that refusals are more common on soft alloy, relative to harder alloys, with all other variables constant.

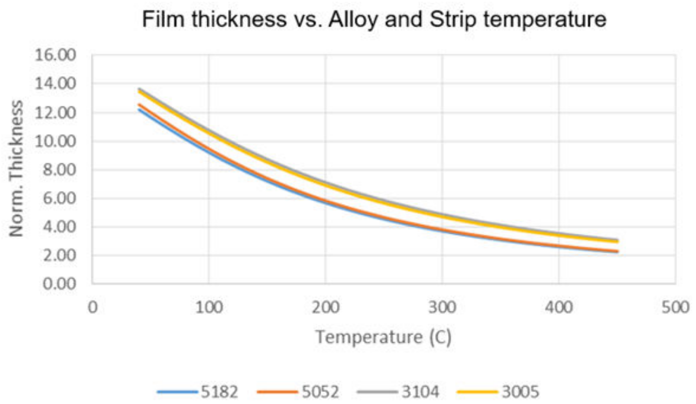

Fig. 14 Graph illustrating the relative impact of alloy (YS) and slab temperature on the film thickness (CoF)

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The same graph also illustrates the impact of slab temperature, with the film thickness increasing with a lower slab temperature.

It is not uncommon to experience an increase in refusals after delays in the rolling process. It is not the bulk slab temperature that should be considered under these circumstances but rather the temperature of the lead and tail ends since the heat losses in these areas are higher than in the body of the slab.

- Mill threading speeds are generally lower than the rolling speed, resulting in more heat loss into the work rolls and work roll coolant on the lead and tail ends.
- There is a greater surface area for heat loss on the lead and tail ends.

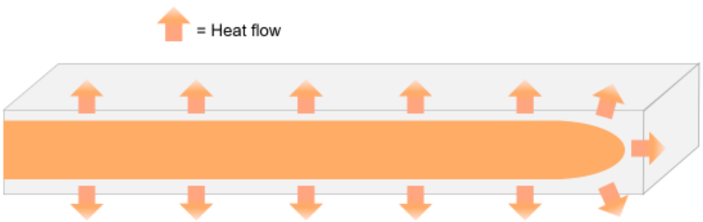

Fig. 15 Heat flow and temperature profile in the body and lead end of a slab

Emulsion properties

The emulsion properties obviously have an impact on the film thickness (CoF), and the relative impact of the following emulsion variables are illustrated in the graphs.

- Emulsion concentration
- Emulsion stability (Particle size distribution PSD)
- Emulsion viscosity
- Contamination by tramp oil (Viscosity change)

Bear in mind that the CoF is inversely related to the film thickness, i.e., the thicker the film the lower the CoF.

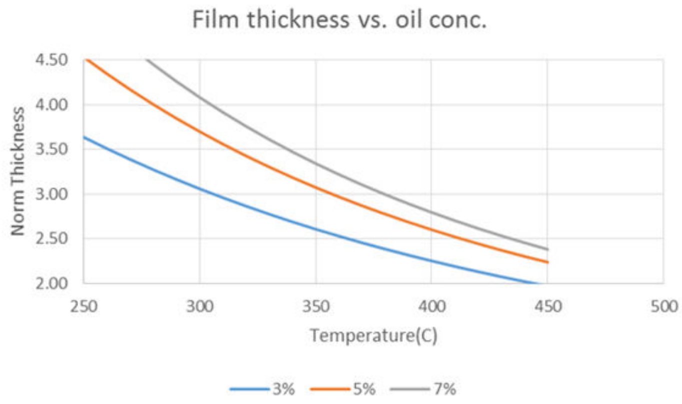

Fig. 16 Graph illustrating the relative impact of oil concentration on the film thickness (CoF).

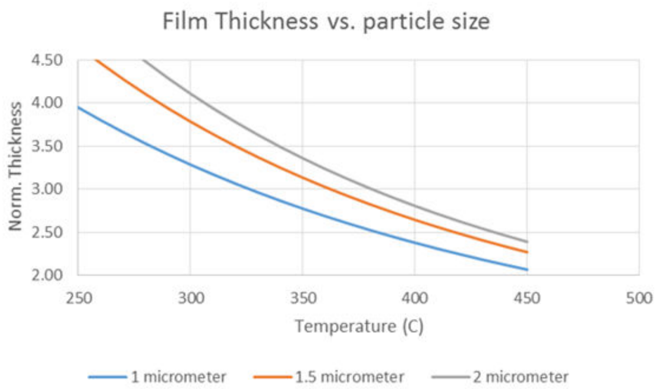

Fig. 17 Graph illustrating the relative impact of emulsion stability (PSD) on the film thickness (CoF).

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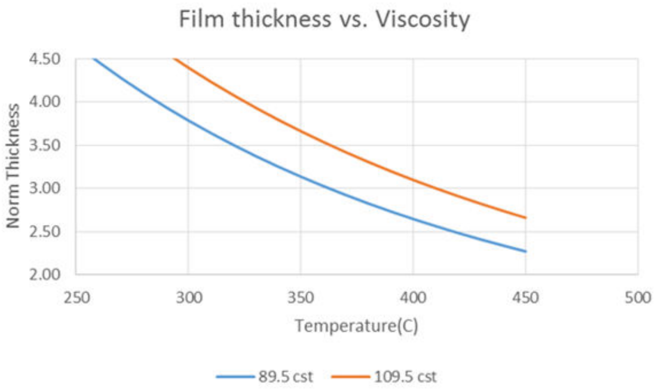

Fig. 18 Graph illustrating the relative impact of emulsion viscosity on film thickness (CoF).

Work roll roughness

As can be expected, work roll roughness has an influence on the CoF. Fig. 19 illustrates the calculated impact on film thickness when the work roll roughness is reduced from 1.6 Ra to 1.3 Ra.

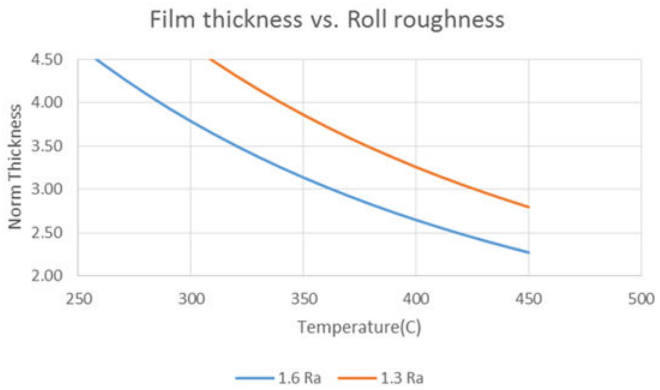

Fig. 19 Graph illustrating the relative impact of work roll roughness (Ra) on film thickness (CoF).

The work roll roughness undergoes a natural reduction through a work roll campaign and this decrease in roughness leads to a decrease in the CoF (an increase in the film thickness).

The main causes for this reduction in work roll roughness are:

- High contact stresses between the work roll and back-up roll, leading to shearing of the peaks on the work roll surface.
- The relative movement between the strip and the work roll surface, leading to wear on the work roll surface.
- Filling of the valleys by work roll coating.

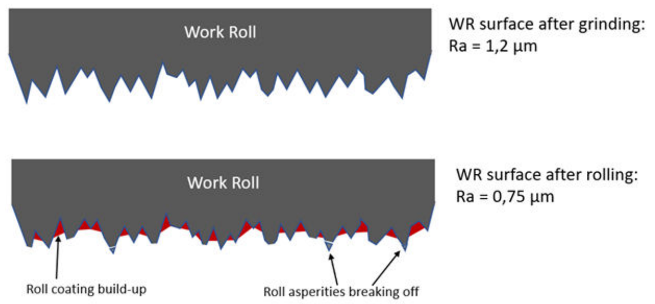

Fig. 20 Schematic of work roll surface texture change through a work roll campaign

Therefore, it is not uncommon to see the incidence of refusals increasing through a rolling campaign, due to a decrease in work roll roughness, and this is often one of the reasons for work roll changes.

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Summary of Controllable Variables

The Table 2 below represents a generalized rating of the identified variables that may impact on refusals.

Table 2 Generalized impact of refusals variables

Variable	Impact	Ability to control
Work roll pass line offset	5	Moderate to high[1]
Tramp oil	4	Moderate to high[1]
Work roll diameter[2]	4	Moderate to high[1]
Slab width[1]	4	Moderate to high[1]
Emulsion viscosity	3	Moderate
Emulsion stability	3	Moderate
Work roll roughness	3	Moderate
Strip temperature	3	Low
Emulsion concentration	2	Moderate

Impact rating				
1	2	3	4	5
Very low	Low	Moderate	High	Very high

Notes for Table 2:

1. The impact of, and ability to control, these variables are dependent on the specific mill design.

2. Work roll diameter impact should be seen in context of the discussion

- The impact assessment and ability to control may vary from rolling mill to rolling mill.
- The 'Ability to control' rating is not only based on the physical ability to control the variable, but also on the freedom of change, given other process and product requirements, such as impact on surface quality.
- To achieve a sustainable solution a change in a combination of the variables may be required.

Other measures

In practice, hot rolling mills apply other ad-hoc measures to overcome refusals. All of these are aimed at either increasing the coefficient of friction ($\uparrow\mu$) at the contact angle or effectively reducing the contact angle ($\downarrow\theta$).

Process action	Objective
Rolling without work roll coolant until the slab is in the roll gap	$\uparrow\mu$
Spraying kerosene onto the work roll to remove free oil	$\uparrow\mu$
Rolling the first few passes without work roll coolant	$\uparrow\mu$
Temporarily adding additional passes to the pass schedule	$\downarrow\theta$
Doing an intermediate reduction on the head end, reversing the	$\downarrow\theta$

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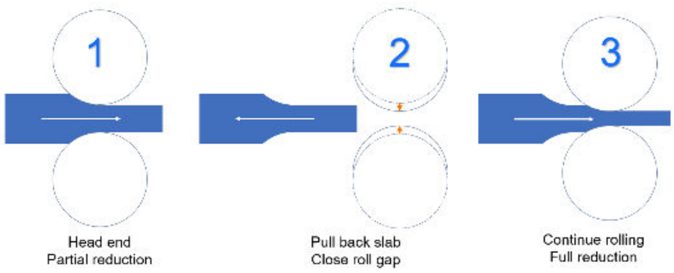

Fig. 21 Schematic of partial reduction of lead end to counteract refusals - not to scale

Conclusion

Slab refusals in aluminum hot rolling are complex and influenced by many factors, including work roll diameter, emulsion properties, mill pass line setup, and more. By understanding the relationships between the contact angle and coefficient of friction, as well as the various controllable variables, rolling mills can take targeted action to prevent refusals and optimize production.

Ultimately, a combination of careful process control, equipment maintenance, and practical adjustments will help reduce the occurrence of slab refusals, leading to smoother, more efficient rolling operations.

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